ENERGY FLOW IN THE UNIVERSE

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Abstract. A brief but broad survey is presented of the flows, forms and large-scale transformations of mass-energy in the universe, spanning a range of about twenty orders of magnitude ($\approx m_{Planck}/m_{proton}$) in space, time and mass. Forms of energy considered include electromagnetic radiation, magnetic fields, cosmic rays, gravitational energy and gravitational radiation, baryonic matter, dark matter, vacuum energy, and neutrinos; sources considered include vacuum energy and cosmic expansion, fluctuations and gravitational collapse, AGN and quasars, stars, supernovae and gamma ray bursts.

1. Global Energy

Everything that happens is a transformation of mass-energy. Starting with inflation and the Big Bang, mass-energy flows through and organizes structures spanning an enormous range of scales— lengths and times from billions of years down to milliseconds. These notes survey the main features of cosmic energy cycles on a global scale and trace the causal links between them.

An absolute luminosity limit for anything is imposed by General Relativity. Suppose a sphere of radius R is filled with light of total mass-energy Mc^2 and released an an instant; the energy has left the sphere after a time R/c, with an average luminosity of Mc^3/R. But the gravity of the energy imposes a limit on how small R can be: if it is smaller than the Schwarzschild radius $R_S = 2GM/c^2$, no light can escape at all since it is within the event horizon of a black hole. The maximum luminosity of any source is therefore

$$L_{GR} = c^5/2G = m_{Planck}^2/2 = 1.81 \times 10^{59} \text{erg sec}^{-1}, \qquad (1)$$

independent of mass. (We have expressed G in terms of the Planck mass $m_{Planck} = \sqrt{\hbar c/G} = 1.2 \times 10^{19}$ GeV $\approx 10^{-5}$g, according to the convention $\hbar = c = 1$. It is tempting call L_{GR} the "Planck Luminosity" since it corresponds to a Planck mass per Planck time, but in fact Planck's constant $\hbar$ cancels out when using units of luminosity— L_{GR} does not depend on quantum mechanics.) This luminosity represents an upper bound on the rate of energy transformation of any kind, on any scale.

For objects within the universe, nothing approaching this luminosity has ever been observed— not because of size, but because radiation interacts with matter (indeed, it must interact to be generated) and therefore takes time to "leak out" of a system. The maximal limiting luminosity requires both an efficiency close to unity and an interaction time close to a light-travel time. Even neutrinos interact more strongly than this in dense collapsing cores of stars where they are copiously produced. The only situation where the limit seems likely to be approached is in production of gravitational radiation from merging black holes of comparable mass, events which may eventually be observable in gravitational waves.[1, 2]

Roughly speaking, the Big Bang saturated the absolute bound L_{GR}. At any time during the early radiation-dominated phase of the early universe, this is about equal to the energy of cosmic radiation within a Hubble volume divided by a Hubble time. If the universe today is dominated by vacuum energy (a cosmological constant or some other form with $\Omega_\Lambda \approx 0.7$)[3, 4], then the "$PdV$ work" being done right now in each Hubble volume is also comparable to L_{GR}. (A comparable rate of transformation occurred during inflation and during reheating.) The cosmic background radiation is less than this today by a factor of about 10^4 because of redshifting.

The comparable amount of energy locked up as rest-energy of Dark Matter has not substantially interacted with anything microscopically for a long time— for most candidates, at least since the weak interactions decoupled. However, a significant flow of energy occurs in the dark matter via gravitational collapse. This energy predates even the cosmic radiation, originating in primordial fluctuations in binding energy which produce cosmic structure, which probably date back to inflation. These perturbations are injecting observable energy flows into the universe today, into the non-vacuum components— the Dark Matter, with $\Omega_m \approx 0.3$, and the baryons, with $\Omega_b \approx 0.03$. Their dimensionless amplitude is about 10^{-5}— this is the fraction of total mass-energy available as free energy in this form. There are of course small flows caused by radiation temperature anisotropies but the dominant effect is gravitational collapse, which in turn creates kinetic motion in the dark matter and causes heating of baryonic gas by compression and shocking. This process heats the bulk of cosmic baryonic matter to temperatures of about $10^{-6} m_{proton} \approx 10^7$ K, creating a pressure suffi-

cient to keep most of the baryons from falling into galaxies and stars.[5, 6] The gas achieves a steady state at this characteristic temperature, where the "hierarchical heating" is balanced by adiabatic losses to the expansion (and thereby slightly modify the global expansion rate.)

Roughly speaking, the cosmic fluctuation amplitude of $Q \approx 10^{-5}$ injects $10^{-5}\rho c^2$ of energy per Hubble time in the cosmic web, with typical velocity scale $Q^{1/2} \approx 10^{-2.5}c$ and typical size $Q^{1/2}/H$ corresponding today to galaxy superclusters. The power in this form of heating is substantial, about 10^{52} erg/sec in the baryons and $10^{53.5}$ erg/sec in the dark matter. Because it radiates inefficiently this dominant reservoir of intergalactic matter is practically invisible except as a diffuse soft X-ray background.

2. Stars

The other forms of energy involve the small fraction of baryons which make it into galaxies. The total density of baryons in galaxies, including all stars and their remnants as well as star-forming gas, adds up to less a quarter of the baryons, or less than one percent of the total density. A small fraction of this material makes it into AGN and supernovae. Somehow the activity is coupled so that these things all contribute roughly comparable total energy budgets.

Most light since the Big Bang has been made by ordinary main-sequence stars. They are still forming from gas, although most of the stars in our past light cone formed about 10^{10} years ago— about 10^{10} of them in each of 10^{10} galaxies in our reference volume, formed over roughly 10^{10} years. Each one lasts for a long time; most of the mass-energy budget is in low mass stars which last for billions of years (10^{10}y for 1 $M_\odot$). The total power in stars in all galaxies over all of cosmic history is now close to being accounted for in cosmic backgrounds from the optical to the far infrared.[7, 8, 9, 13] The distribution in time is estimated from redshifts of directly imaged galaxies[10] and the backgrounds are now close to being resolved, so the spacetime distribution of the source populations are close to accounted for. The total flux is about 1/30 of the cosmic background radiation, approximately equally distributed between direct light from stars and reradiated light from obscuring dust, and mostly radiated since a redshift of about two, when the universe was three times smaller than today.

This energy ultimately derives mostly from the conversion of hydrogen to helium, with some contribution from synthesis to heavier elements. The enrichment history is recorded as fossil abundances in stars and can also be traced directly in high-redshift absorption systems[11]. The total amount of light agrees with the total production of elements by stars[13] if the metals are mostly ejected from the stellar parts of galaxies and join the dominant

intergalactic gas. This large-scale sharing of metals is confirmed from X-ray line emission in galaxy clusters[12].

Stellar formation as well as stellar instabilities (important especially at the end of the stable nuclear burning stage) all occur at roughly the Chandrasekhar mass, corresponding to a number of protons

$$N_C = 3.1(Z/A)^2(m_{Planck}/m_{proton})^3 \approx 10^{57} \tag{2}$$

(shown here with its classical definition as the limiting mass of an electron-degeneracy-supported dwarf; Z and A are the average charge and mass of the ions, typically $Z/A \approx 0.5$ and $M_C = 1.4M_\odot$, where $M_\odot = 1.988 \times 10^{33}g \approx 0.5M_*$ is the mass of the Sun.) One way or another the large numbers in Table 1 for baryonic flows all ultimately derive from the large number $(m_{Planck}/m_{proton}) \approx 10^{19}$; this is true even for the global cosmological quantities, since the age of the universe now is about the lifetime of a star.

3. Quasars

In the centers of galaxies, a small fraction of material (up to about 10^{-2} of the stellar mass, so on the order of 10^{-4} of the total mass-energy) accumulates and organizes itself into a different kind of engine, called quasars, active galactic nuclei or AGN, which generate their enormous power from gas interacting with massive black holes. Although events can occur in quasars quickly (on timescales of days or less, the Schwarzchild time for the massive holes) the bright phase lasts for tens of millions of years, determined by the behavior of the surrounding gas. The bright activity of quasars peaked at redshifts of about two and is much less today[14], but the black hole remnants of 10^6 to $10^9 M_\odot$ reside still in the centers of most galaxies including our own.[15] The total number N of quasars is thus about the same as the number of galaxies, with a tendency for large bright ones to lie in the biggest galaxies. The overall energy from quasars is not much less than that from stars, due to their large efficiency in converting rest-mass into energy. They dominate the energy budget of the universe for most hard radiation such as X-rays and gamma rays (with some competition from supernovae), and are mainly responsible for ionizing the intergalactic gas.[16]

Active nuclei derive all of their electromagnetic energy from gravity—either from the binding energy of the infalling material, or from the rotational energy of the black hole.[17, 18, 19] Gas falls in and forms a disk near the hole, fattened by heating into a torus or corona. Magnetic fields help to extract the orbital and spin energy and also to channel some of it into "Poynting jets" of relativistic matter moving so close to the speed of light that a particle's kinetic energy is many times its rest mass, with Lorentz

factors of $\Gamma = E/mc^2 \approx 10$. Light emerges at all wavelengths, from radio to gamma rays, reflecting activity on many scales and nonthermal radiative processes involving relativistic particles, magnetic fields and bulk kinetic energy of matter. There should be a comparable luminosity in cosmic rays, a small portion of which is channeled into high energy neutrinos.

The accretion rate of matter and hence the luminosity is approximately regulated by feedback on the gas accretion. For both AGN sources and massive stars the characteristic luminosity is the Eddington limit, $L_E = 3GMm_pc/2r_e^2 = 1.25 \times 10^{38}(M/M_\odot)$ erg/sec (where the classical electron radius $r_e = e^2/m_ec^2$), above which radiation pressure outwards on ionized gas exceeds gravitational attraction; brighter sources tend to disassemble themselves. An Eddington-limited source lasts a Salpeter time $Mc^2\epsilon/L_E = 4 \times 10^8\epsilon$ y, which is independent of mass but does depend on the overall efficiency ϵ of extracting rest mass Mc^2, which may be as large as tens of percent for material near a black hole. Significant variability occurs on all timescales down to the Schwarzschild time of the black hole, $R_S/c = 10^{-5}\text{sec}(M/M_\odot) = 100\text{sec}(M/10^7M_\odot)$.

Because mergers of galaxies are common, it is likely that mergers of their central holes are common. If 10^{10} galaxies within the Hubble volume each merge about once per Hubble time, there is about one such event per year in our past light cone, releasing about 10^{62} ergs for a $10^8M_\odot$ hole. Such an event, with a luminosity of $\approx L_{GR}$, far outshines all other sources put together for a Schwarzschild time (on the order of minutes for a $10^8M_\odot$ hole). Even at an average rate of one per year, the gravitational wave luminosity of the universe radiated from these mergers is on average comparable to all the other forms of energy combined, stars and everything. These waves have not yet been detected, but they are in principle easily detectable with spaceborne gravitational wave detectors such as LISA[21].

4. Superstars and Supernovae

Smaller but equally violent energy releases occur as byproducts of instabilities in dead or dying stars. When a star exhausts the nuclear fuel in its core, it is no longer stable; the core collapses seeking a new equilibrium, and the release of energy from this collapse blows off the enveloping material. The outcome depends on the mass and composition of the star. A small star like our Sun will blow off about half of its mass, the rest of it left behind in a white dwarf, a glowing ember of still-unburned nuclear fuel (e.g. He, C, N, O, Ne,...), about 10,000 km diameter (about the size of the Earth) and a million times the density of ordinary matter, stabilized by electron degeneracy pressure against gravity. More massive stars create iron cores above the Chandrasekhar limit of $1.4M_\odot$ at which electron degeneracy support

fails, and collapse to a neutron star with a diameter of only about 10 km and the same density as an atomic nucleus. Massive cores above a few solar masses cannot be supported by neutron degeneracy or gluon pressure, and collapse all the way to black holes.

Collapse of these remnants releases gravitational binding energy. Smaller and denser objects create more ($\propto 1/r$) and faster ($\propto \rho^{-1/2}$) energy release. White dwarf formation ejects a planetary nebula at high velocity; neutron star formation leads to a Type II supernova explosion.[20] Other spectacular effects occur when remnants live in binary systems and perform a whirling dance with normal stars or with each other. Accretion onto compact remnants from companion stars leads to cataclysmic X-ray sources, and accretion onto a white dwarf can trigger a nearly complete nuclear deflagration and disruption, leading to a Type Ia supernova.[22]

The scale of energy budgets of cataclysms derives from the mass-energy of the stellar remnants, with a basic scale set by the rest mass of the sun $M_\odot c^2 = 1.8 \times 10^{54}$ ergs. The nuclear energy available from a white dwarf is about 10^{51} ergs, most of which is liberated when a Type Ia supernova explodes, mostly as blast energy. The binding energy of a neutron star is about $10^{53.5}$ ergs, almost all of which is radiated as neutrinos during a Type II supernova. (These were directly detected from supernova 1987a; the sum of such events over the Hubble volume leads to a soon-to-be-detectable neutrino background[23, 24].) A small fraction of the neutrinos as well as a bounce shock from the neutron star couple to the enveloping material, dumping heat which ejects it at high velocity. About 10^{51} erg emerges as blast energy, less than ten percent of this as light. Heat, light, heavy elements, magnetic fields, kinetic motion and cosmic rays all carry a substantial amount of energy far away and spread over a volume vastly larger than their source, providing a regulatory cycle and coupling of energy and material flow.

The overall energy budgets of the supernovae are again surprisingly close to that of the stars and AGNs, although most of the SN energy budget is emitted in neutrinos, with a small fraction as blast energy and an even smaller fraction as light. Even though only about a percent of stellar mass participates in supernovae, the ν production efficiency is much higher than nuclear energy (≈ 0.1 as opposed to 0.007). Although the energy sources for the different types of supernovae are completely different (and the Type Ia even leaves no compact remnant), their blast energies are similar. Both eject a substantial mass of chemically enriched and freshly-made radioactive material which powers a glow lasting for months. Also by coincidence, the cosmic rates of the different types of supernovae are comparable in spite of the very different progenitors; SNeIa are just a few times brighter, and a few times rarer, than SNeII.

5. Fireballs and Hypernovae

Long shrouded in mystery, gamma ray bursts now seem to make use of the same compact remnants and combine features of both supernovae and of quasars. Apparently, even these most exotic of sources do not require new cast— only new roles, new settings and combinations for the familiar players, neutron stars and black holes. They are a kind of naked spinning supernova and miniature quasar wrapped into one.

The main event in a gamma ray burst is a "relativistic fireball."[25, 26] A burst of much energy in a small space results in an expanding plasma of photons, electrons and positrons, neutrinos and antineutrinos. There is enough scattering for matter to behave like a fluid, though few enough baryons (less than $10^{-4}M_\odot$) not to inhibit acceleration with particle rest energy, so the relativistic fluid expands very close to the speed of light, with a Lorentz factor $\Gamma \geq 100$. The kinetic energy is dissipated in shocks and radiated as gamma rays at radii of $10^{13} - 10^{15}$ cm, the scale of the solar system. Because of Lorentz beaming any observer sees at most a small relativistically-blueshifted patch of the fireball, allowing rapid variability. (The fireball may also itself be beamed, visible only from some directions.) The interaction with the environment as well as the beaming leads to a wide variety of events, with variability down to milliseconds but a duration up to hundreds of seconds, and optical afterglows which remain observably bright for a few days— as large a temporal dynamic range as in a quasar, but scaled small. The energy of the brightest gamma ray bursts is typically estimated in both gamma rays and optical afterglow energy to be $10^{53.5}$ erg[28] (or in extreme cases $10^{54.5}$ erg, assuming isotropic emission; allowing for anisotropic beaming, the total energy budget could well be less than this.)

The fireball, like a supernova, is created by a cataclysmic combination of stellar remnants. A favorite current model invokes a stellar-mass black hole or neutron star surrounded by a torus of neutron-density material— essentially, a donut-shaped neutron star surrounding a more massive black hole.[29, 30] This donut+hole system resembles a very dense, scaled-down version of the quasars, with magnetic fields, now in combination with the highly dissipative neutrinos, extracting energy from the spin of a black hole and/or the orbital energy of the torus. The Schwarzchild time for a $10M_\odot$ hole is 10^{-4} sec so the smallest timescales can be explained; as in quasars the disk and the event last for much longer than this dynamical time.

A spinning black hole can liberate up to $0.29Mc^2$ or 5×10^{54} ergs for a $10M_\odot$ hole; material in a disk can liberate up to $0.42Mc^2$ or 10^{53} ergs for a $1M_\odot$ disk. There is thus ample energy in a stellar-mass "microquasar" to power the high-Γ burst of gamma rays and a lower-Γ optical afterglow.

It seems likely that beaming should often produce the latter without the former— a new population of objects which would lack gamma rays, perhaps appearing like short-lived, very bright SNeII. These may have already been noticed in distant supernova surveys [3, 4] but in any case are not common (at most about 10^3 per day) so they are likely not important in the overall energy budget.

It is not clear exactly how this configuration is produced, but several ideas fit well into stellar evolution scenarios. One model is a "hypernova"[31], which is like a particularly massive Type II supernova core collapse but with a collapse of some of the material inhibited or delayed by rotation. The middle forms a black hole, some of the rest forms the neutron torus. Alternatively, two neutron stars in a close binary (themselves formed from earlier supernova explosions) might eventually coalesce by gravitational radiation of their orbital energy; the mass can exceed the maximum mass of a stable neutron star, leading to a black hole surrounded by a dense neutron torus.[32] Either of these scenarios plausibly leads to the enormous magnetic fields required to form a microquasar. One way to distinguish them observationally is by observing where the bursts occur: the first picture produces a burst after only tens of millions of years, while the second may be after billions of years, and should produce bursts far from star-formation regions.[31]

TABLE 1. Scales of Time, Energy, and Power in the Universe

Energy source	Luminosity $L/$ object (erg/sec)	Duration $D/$ flash	Rate R $= NH$	N_{active} $= NHD$	Energy $E = DL$ (erg)	Power $I_{tot} = RE$ (erg/sec)	total N in V_0/H_0 $= R/H$
Big Bang	$\approx 10^{59}$	10^{12}sec	$1/10^{12}$sec	1	10^{71}	10^{59}	1
Λ	10^{59}	10^{10} y	$1/10^{10}$ y	1	10^{76}	10^{59}	1
$Q = 10^{-5}$	10^{46}	10^{10} y	$1/10^{2.5}$y	$10^{7.5}$	10^{65}	10^{54}	$10^{7.5}$
Stars ($1M_\odot$)	$10^{33.5}$	10^{10} y	10^{10}/y	10^{20}	10^{51}	$10^{53.5}$	10^{20}
AGN($10^7 M_\odot$)	10^{45}	10^{15} sec	1/y	$10^{7.5}$	10^{60}	$10^{52.5}$	10^{10}
AGN($10^9 M_\odot$)	10^{47}	10^{15} sec	0.01/y	$10^{5.5}$	10^{62}	$10^{52.5}$	10^{8}
GW($10^8 M_\odot$)	10^{59}	1000 sec	1/y	$10^{-4.5}$	10^{62}	$10^{54.5}$	10^{10}
SNeII(ν)	10^{53}	seconds	1/sec	1	10^{53}	10^{53}	$10^{17.5}$
SNe(O/IR)	10^{43}	$10^{6.5}$ sec	1/sec	$10^{6.5}$	$10^{49.5}$	$10^{49.5}$	$10^{17.5}$
GRB(γ)	10^{53}	seconds	1/day	10^{-5}	10^{53}	10^{48}	$10^{12.5}$
GRB(O/IR)	10^{48}	10^{5}sec	1/day	1	10^{53}	10^{48}	$10^{12.5}$

6. Energy Budgets

Table 1 shows a broad summary of energy flows of various kinds: the cosmic microwave background; the accelerating universe; the free energy injected by cosmological fluctuations and gravitational instability; normal stars in galaxies; small and large active galactic nuclei; gravitational waves from mergers of AGN engines in galaxy mergers; neutrinos from core-collapse supernovae; optical radiation and blast energy from Type I and Type II supernovae; gamma ray and optical emission from gamma ray bursts. Except for the Big Bang (which refers to the radiation-dominated epoch of the universe), entries in the table refer to events at moderate redshift (less than a few) out to distances of the order of the Hubble distance cH_0^{-1} or about 14 billion light-years for a Hubble constant $H_0 = 70$km sec^{-1} Mpc^{-1}, in a reference "Hubble Volume" $V_0 \equiv 4\pi c^3 H_0^{-3}/3 = 3 \times 10^{11}$Mpc^3, containing about $10^{9.5}$ giant galaxies (with a luminosity $\approx 2 \times 10^{10} L_\odot$ each), and a spacetime volume V_0/H_0. Within this spacetime volume there have been about N events of each kind, from one Big Bang to 10^{20} stars. The numbers represent order-of-magnitude averages over moderate redshifts $0 \leq z \leq 3$, which includes the bright epochs of star formation and quasars. The entries show the luminosity L of each single event; the typical duration D of each event; the rate R at which new events appear; the number N_{active} of events active at any given time; the energy E released in the designated form by each object; the power I_{tot} produced by each population in the entire Hubble volume; and the total number N in the Hubble spacetime volume. The ubiquitous appearance of numbers like $\approx 10^{20}$ can be traced in all cases to $m_{Planck}/m_{proton} \approx 10^{19}$. Not shown are the timescales of most rapid variation; for each source this has a dynamic range of order $(m_{Planck}/m_{proton})^{1/2}$, extending for quasars down to less than a day and for compact sources down to small fractions of a second. Recall that one day=10^5 sec, one month=$10^{6.5}$ sec, one year=$10^{7.5}$ sec. For AGN and GRB, the energy budgets in kinetic energy, Poynting flux, and cosmic rays are comparable to the nonthermal electromagnetic budgets shown; for supernovae, these forms are somewhat less. The largest energy by far is the work being done by the cosmological constant negative pressure in creating new vacuum energy, which replaces the bulk of the entire mass-energy content of the universe in a Hubble time.

7. Cosmic Ecology

A glance at I_{tot} in table 1 shows a remarkable coincidence: in spite of 20 orders of magnitude variation in mass and timescale (and N), the integrated power is comparable for all of these populations if we count the GRB's as a subclass of supernovae. This coincidence can be understood if

there are feedback loops controlling the release of energy— a globally regulated choreography coupling the formation rate of stars, the events leading to their death and the transformation and ejection of the elements, the formation of galaxies and quasars and the feeding of their central engines.

This may be just a coincidence, or it may be a hint that stars, galaxies and indeed the universe behave as "whole systems" controlled by nonlocal interactions between interdependent parts spanning a large range of scales. Many mechanisms are available to provide the coupling: radiation, magnetic fields[33], cosmic rays, and fast fluid flows. Although the scales of the individual sources all derive directly from fundamental physics, their frequency in the cosmos depends on this poorly understood "cosmo-ecology" of interacting systems.

Another point is the sheer dynamism of the sky on all timescales. The rate R of many new events include a range, from seconds to years, accessible to direct surveys. Somewhere in the sky a new observable supernova appears every second, with over a million brightly shining at any time; on average a new quasar appears every year, with tens of millions shining at any time. The dynamic range of variability includes a range, from milliseconds (for GRB's) to years (for quasars), accessible to direct monitoring. Astronomical and data exploration techniques have hardly started to sample what is happening.

Have we seen it all, thought of everything that could happen, already explored the entire range of things that could be happening out there? These questions hang in the air whenever new experiments are contemplated, and for some large projects, such as gravitational wave detectors, are major strategic concerns.[1, 2, 21, 34, 35] As the experience with gamma ray bursts shows, for even the most exotic sources the ancient optical band still holds vital information for uncovering the physics of the sources. There are almost certainly new combinations of familiar players (such as flares of stars being eaten by dead quasar black holes) which exist but are not yet found. Microlensing[36] and supernova surveys[3, 4] have shown what CCD arrays and data-mining can do; these technologies promise to expand the scope, depth and precision of the digital exploration of the time domain by orders of magnitude in the next few years and reveal a still richer phenomenology.[37]

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